Net energy content of rice bran, defatted rice bran, corn gluten feed, and corn germ meal fed to growing pigs using indirect calorimetry[1]

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ABSTRACT: The objective of this experiment was to determine the effects of increased fiber content in diets on heat production (HP) and NE:ME ratio and to determine the NE content and NE:ME ratio of full-fat rice bran (FFRB), defatted rice bran (DFRB), corn gluten feed (CGF), and corn germ meal (CGM) fed to growing barrows using indirect calorimetry (IC). Thirty growing barrows (28.5 ± 2.4 kg BW) were allotted in a completely randomized design to 5 dietary treatments that included a corn–soybean meal basal diet and 4 experimental diets with a constant ratio of corn and soybean meal (difference method) containing 30% FFRB, DFRB, CGF, and CGF. Pigs were housed in individual metabolism crates for 20 d including 14-d adaptation to the diet and 6 d to determine the HP and total collection of feces and urine in respiration chambers. Pigs were fed their respective diets at 550 kcal ME·kg BW$^{0.60-1}$·d^{-1} on the basis of BW measured on days 0, 7, and 14. The apparent total tract digestibility (ATTD) of DM, GE, and OM were greater ($P < 0.01$) in pigs fed the basal diet. The ATTD of DM, GE, and OM in pigs fed the DFRB diet were lesser ($P < 0.01$) when compared with those fed the basal and FFRB diets. The ATTD of ether extract (EE) in pigs fed the FFRB diet was greater ($P < 0.01$) compared with those fed basal, DFRB, CGF, and CGM diets. The HP adjusted for the same ME intake was greater ($P < 0.01$) in pigs fed the DFRB, CGF, and CGM diets compared with those fed basal and FFRB diets. The NE:ME ratio in pigs fed the FFRB diet was greater ($P < 0.01$) when compared with those fed the DFRB, CGF, and CGM diets. The NE content of FFRB, DFRB, CGF, and CGM determined using the IC method were 2,952, 1,100, 1,747, and 2,079 kcal/kg DM, respectively. The NE content of FFRB, CGF, and CGM determined using the IC method were 3.5%, 3.8%, and 1.8% greater, respectively, than the predicted values, whereas NE content of DFRB determined using the IC method was 2.1% lower than the predicted values. In conclusion, pigs fed the fiber-rich ingredients had greater HP and lower nutrient digestibility. However, pigs fed FFRB diets containing greater fat content had a lower heat increment and, therefore, higher utilization efficiency. The NE:ME ratio ranged from 71.6% to 82.4%. The NE of FFRB, DFRB, CGF, and CGM determined using the IC method were 2,952, 1,100, 1,747, and 2,079 kcal/kg DM, respectively.

Key words: coproduct, growing pig, heat production, indirect calorimetry, net energy

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INTRODUCTION

Full-fat rice bran (**FFRB**) is a coproduct of rice grain production consisting primarily of the outer layers of the grain (Salunkhe et al., 1992). Alternatively, the fat may be removed from FFRB using solvent extraction to produce defatted rice

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bran (**DFRB**) with a fat content of 2% to 4% (Stein et al., 2016). Corn germ is produced from wet milling of corn, where the germ is separated from the corn kernel during the initial steps before starch is removed (NRC, 2012). The resulting defatted corn germ is called corn germ meal (**CGM**), which typically contains <3% crude fat. Corn gluten feed (**CGF**) is also a coproduct of the wet milling industry and is the corn kernel that remains after the extraction of most of the starch, germ, and gluten for production of corn starch or corn syrup (NRC, 2012). Both of these corn coproducts have high content of fiber and protein (Anderson et al., 2012). The global production of corn and rice exceeded 1,000 million and 700 million tons per year (Statista, 2015; Stein et al., 2016), respectively, thereby producing large quantities of grain coproducts (Jaworski et al., 2015) from the rice and corn processing industries. Although a large number of grain coproducts are used for animal feeding every year (Stein et al., 2015), there are minimal reports of NE values of grain coproducts in growing pigs.

Among the available energy evaluation systems, the NE system provides a more accurate estimate of the dietary energy available to the animal (Noblet and Van Milgen, 2004; Velayudhan et al., 2015), especially for fiber-rich feeds and ingredients (Noblet et al., 1994; Noblet and Le Goff, 2001). In the current study, FFRB, DFRB, CGF, and CGM contain relatively high concentrations of dietary fiber; therefore, it is necessary to determine their NE value for effective utilization in swine diets (Kim and Nyachoti, 2017). A series of NE prediction equations generated by Noblet et al. (1994) are widely used to calculate the NE of ingredients, and it is necessary to validate the equations. The effect of fiber level on heat production (**HP**) in pigs is inconsistent with previous studies (Jørgensen et al., 1996; Noblet and Le Goff, 2001; Rijnen et al., 2003; Kim and Nyachoti, 2017), while dietary fat seems to reduce the HP (Noblet and Le Goff, 2001; Li et al., 2017b).

Therefore, the objectives of this experiment were to 1) determine the effect of increased fiber content in diets on HP and NE:ME ratio and 2) determine the NE and NE:ME ratio of FFRB, DFRB, CGF, and CGM fed to growing pigs using the difference method.

MATERIALS AND METHODS

All experimental protocols including animal care and use were approved by the Institutional Animal Care and Use Committee of China Agricultural University (Beijing, China).

Experimental Animals and Diets

Thirty growing barrows [Duroc male × (Large White male × Landrace female)] with an average initial BW of 28.5 ± 2.4 kg were used in this experiment conducted at the FengNing Swine Research Unit of China Agricultural University (Hebei Province, China). The pigs were individually housed in adjustable stainless-steel metabolism crates with a feeder and a nipple drinker and located in a temperature-controlled room (22 ± 2 °C). The 5 experimental diets with a constant corn:soybean meal ratio included a corn–soybean meal basal diet and 4 test diets formulated to contain 30% FFRB, DFRB, CGF, or CGM, which, respectively, replaced 30.88%, 30.78%, 31.57%, and 31.10% of the energy supplied by corn, soybean meal, and AA.

Experimental Design and Procedure

The experiment was conducted in 5 consecutive periods (6 pigs per period) using the same facility and similar experimental conditions and procedures because 6 indirect calorimetry (**IC**) chambers were available. Each experiment period included a 14-d diet adaptation period and a 6-d HP measurement period. In the first period, the basal diet was fed to 2 pigs and other diets were fed to 1 pig each, and in the second period, the FFRB was fed to 2 pigs and other diets were fed to 1 pig each, and so on such that each diet was fed to 6 pigs.

Pigs were fed their assigned diets at 550 kcal ME·kg $BW^{0.60-1}$·d^{-1}based on BW measured on days 0, 7, and 14, which was closed to ad libitum feed intake. Pigs were fed equal-sized meals twice daily at 08:30 and 15:30 h using automatic feeders. On day 14, pigs were subsequently transferred to the open-circuit respiration chambers for continuous measurement of daily O_2 consumption and CO_2 and CH_4 production. On the last day of each period (day 19), pigs were fasted; the HP measured during the last 8 h from 22:30 h (day 19) to 06:30 h (day 20) was considered as fasting HP (**FHP**). During each period, feed refusals and spillage were collected once daily and subsequently dried and weighed. From days 15 to 19, total feces and urine were collected and removed from the chamber once daily in the morning for the determination of DE and ME of the experimental diets. On day 20, only urine was collected for the determination of FHP.

Collected feces were stored at −20 °C. Urine collection was initiated at 08:30 h on day 15 and ceased at 08:30 h on day 20. Urine was collected (in plastic containers containing 50 mL of 6 N HCl to minimize nitrogen losses) and weighed on removal from the chamber. Urine volume (measured as weight) was determined each day and a 10% daily aliquot was stored at −20 °C.

Details on the open-circuit respiration chambers and IC method were reported by Zhang et al. (2014) and Van Milgen et al. (1997), respectively. In the current study, 6 open-circuit respiration chambers with a volume of approximately 7.8 m^3 were used, and the construction of these chambers was based on a design described by Van Milgen et al. (1997). The temperature was maintained at 22 °C in the fed state and was increased to 24 °C during the fasted state. The relative humidity was controlled at 70%. A 10-h lighting schedule was used. The analyzers had a range of measurement of 19.5% to 21% for O_2, 0% to 1% for CO_2, 0% to 0.1% for CH_4, and 0% to 0.1% for NH_3 with a sensitivity of 0.2% within the measurement range. The gas extraction rate was measured by a mass flow meter (Alicat, Tucson, AZ). Gas concentrations in each chamber were measured at 5-min intervals. Two respiration chambers shared 1 gas analyzer. The O_2 was measured with a paramagnetic differential analyzer (Oxymat 6E; Siemens, Munich, Germany), whereas CO_2, CH_4, and NH_3 were measured with infrared analyzers (Ultramat 6E; Siemens). The sensor responses were standardized and calibrated by applying a series of prepared standard gases to span the measurement range of the sensors. The specific procedures followed the brochure of the sensors (Oxymat 6E and Ultramat 6E) manufactured by Siemens (Munich, Germany). The standard gases used included 20.000% O_2 (in 80.000% N_2) or 0% CO_2 and 0% CH_4 (in 100% N_2) for zero calibration and 20.932% O_2 (in 79.068% N_2) or 0.8% CO_2 and 0.02% CH_4 (in 99.18% N_2) for span calibration.

Sample Preparation and Chemical Analyses

All ingredients were collected at the preparation of diets to measure the DM of each ingredient. Diets were collected after preparation to analyze chemical composition. The diets were also collected during each collection period to measure the DM of diets. Fecal samples were oven-dried for 72 h at 65 °C and were ground through a 1-mm screen before chemical analysis. At the end of collection period, urine samples were thawed and pooled separately for each pig.

The DM content of ingredients, diets, and feces was determined by drying 5 g of samples in a forced-air oven (model GZX-9140 MBE; Boxun Company, Shanghai, China) at 105 °C to a constant weight (method 934.01; AOAC, 2006). Samples of all diets, urine, and feces were analyzed for CP (method 984.13; AOAC, 2006) using an apparatus (Foss Kjeltec 2100, Foss Kemao Inc., Beijing, China). The GE in the samples of ingredients, diets, feces, and urine was determined using an isoperibol calorimeter (Parr 6300 Calorimeter, Moline, IL) with benzoic acid as a standard. The nitrogen content in samples of ingredients, diets, feces, and urine was determined according to the standard procedure (method 984.13; AOAC, 2006). Sample was digested in H_2SO_4, using $CuSO_4$ as catalyst, converting nitrogen to NH_3, which was distilled and titrated, and CP was calculated as nitrogen × 6.25. The ether extract (**EE**) content in samples of ingredients and diets was determined using the petroleum ether extraction method (Thiex et al., 2003) by an automated analyzer (Ankom XT15 Extractor; Ankom Technology, Macedon, NY). The NDF and ADF contents in samples of ingredients, diets, and feces were determined using a fiber analyzer (model A220 fiber analyzer; Ankom Technology, Macedon, NY) following a modification of the procedure by Van Soest et al. (1991). The concentration of NDF was analyzed using heat-stable α-amylase and sodium sulfite without correction for insoluble ash. Samples of all ingredients, diets, and feces were also analyzed for ash by burning carbonized samples at 550 °C for 8 h until light gray ash results, or to constant weight (method 923.03; AOAC, 2006). Total dietary fiber (**TDF**) and insoluble dietary fiber (**IDF**) in the ingredients and diets were analyzed by using a combination of enzymatic and gravimetric procedures (Prosky et al., 1992). Dietary fiber values (IDF and TDF) were calculated as the weight of residue minus the weight of protein and ash. The concentration of soluble dietary fiber (**SDF**) in the ingredients and diets was calculated as the difference between TDF and IDF. The P in the ingredients and diets was analyzed according to the vanadate colorimetric method (method 946.06; AOAC, 2006) using a spectrophotometer (Spectrumlab 721s; Lengguang Company, Shanghai, China). All diets and ingredients were analyzed for Ca (method 968.08; AOAC, 2006) by an atomic absorption spectrometer (Hitachi Z-2000; Hitachi Ltd., Tokyo, Japan). The starch content in ingredients and diets was analyzed according to the enzymatic method described by Xiong et al. (1990).

In brief, the ingredients and diets were hydrolyzed with 6 N HCl at 110 °C for 24 h and analyzed for 15 AA using an Amino Acid Analyzer (Hitachi L-8900; Hitachi Ltd., Tokyo, Japan). Methionine and cysteine were determined as methionine sulfone and cysteic acid after cold performic acid oxidation overnight and hydrolyzing with 7.5 N HCl at 110 °C for 24 h (Llames and Fontaine, 1994; Commission Directive, 1998) using an Amino Acid Analyzer (Hitachi L-8800, Hitachi Ltd., Tokyo, Japan). Tryptophan was determined after LiOH hydrolysis for 22 h at 110 °C (Commission Directive, 2000) using high-performance liquid chromatography (Agilent 1200 Series; Agilent Technologies Inc., Santa Clara, CA).

Calculations

The DMI from days 15 to 19 in each period was calculated as the product of feed intake and DM content of diets. The intake of GE was calculated as the product of the GE content of the diet and the actual feed DMI over the 5-d collection period from days 15 to 19. The energy lost in feces, urine, and methane were measured for each animal. The ME was calculated by subtracting energy in the urine and methane from DE. Energy lost as methane was calculated using the 9.45 kcal/L conversion factor (Brouwer, 1965).

The apparent total tract digestibility (**ATTD**) of energy and nutrients (Noblet et al., 1994), total HP (**THP**; Brouwer, 1965), FHP (Brouwer, 1965), retained energy (**RE**; Noblet et al., 1994), and NE values (Noblet et al., 1994) in diets were calculated using the following equations:

$$\mathrm{ATTD} = [(\mathrm{Fi} - \mathrm{Ff})/\mathrm{Fi}] \times 100\%, \tag{1}$$

where Fi = the total intake of energy (kilocalories) or nutrients (gram) corresponding to collection period and Ff = the total fecal output of energy (kilocalories) or nutrients (gram) corresponding to collection period.

$$\mathrm{THP} = 3.87 \times \mathrm{O_2} + 1.20 \times \mathrm{CO_2} - 0.53 \times \mathrm{CH_4} - 1.43 \times \text{urinary nitrogen excretion}, \tag{2}$$

where THP is in kilocalories, O_2 = oxygen consumption in liters, and CO_2 = carbon dioxide production in liters. Urinary nitrogen excretion is in grams. During days 15 to 19 of each period, O_2, CO_2, and CH_4 concentrations in both ingoing and outgoing air, and outgoing air flow rates were measured at 5-min intervals. These data were then used to calculate O_2 consumption and CO_2 and CH_4 production during each 5-min interval and these values were averaged and extrapolated to a 24-h period. In addition, FHP was calculated using the equation for THP with gas concentrations and air flow obtained from only the last 8-h HP measurement from days 19 to 20 (i.e., from 22:30 to 06:30 h). To base production using the same time span as used for THP, the 8-h HP was extrapolated to a 24-h period.

$$\mathrm{RE} = (\text{ME intake} - \mathrm{THP}), \tag{3}$$

where RE is in kilocalories per day and ME intake and THP are in kilocalories per day. The RE as protein (**$\mathrm{RE_P}$**) was calculated from nitrogen retention (nitrogen × 6.25 × 5.70, kcal/g), whereas the amount of the RE as lipids (**$\mathrm{RE_L}$**) was calculated as the difference between RE and $\mathrm{RE_P}$.

$$\mathrm{NE} = (\mathrm{RE} + \mathrm{FHP})/\mathrm{DMI}, \tag{4}$$

where NE is in kilocalories per kilogram DM; RE and FHP are in kilocalories per day; and DMI is in kilograms per day.

The DM of ingredients was measured at the preparation of diets to calculate the DM ratio of each test ingredient in the diet. The DM of minerals and vitamins in the basal diets was 2.97% and considered not to supply any energy; therefore, the DE, ME, and NE of the basal diet were divided by 0.9703 (the DM ratio of corn, soybean meal, and AA in the basal diet) to calculate the DE, ME, and NE of the corn and soybean meal mixture. The difference method (Adeola, 2001) was used to calculate the average GE, DE, ME, and NE contributions of test ingredients from the mean GE, DE, ME, and NE contents of each respective diet and assuming that the average GE, DE, ME, and NE of the corn and soybean mixture obtained for the basal diet was applied to the other experimental diets. The DE:GE, ME:DE, and NE:ME ratios could then be calculated for test ingredients from these calculated GE, DE, ME, and NE values and used to estimate the final DE, ME, and NE values as the product of measured GE and DE:GE for DE, measured GE and DE:GE and ME:DE for ME, and measured GE and DE:GE, ME:DE, and NE:ME for NE. All calculations were on a DM basis. The RQ was calculated as the ratio between CO_2 production and O_2 consumption. The NE of the test ingredients were calculated according to the prediction equations established by Noblet et al. (1994):

$$\mathrm{NE} = 0.700 \times \mathrm{DE} + 16.1 \times \mathrm{EE} + 4.8 \times \mathrm{ST} - 9.1 \times \mathrm{CP} - 8.7 \times \mathrm{ADF}, \tag{5}$$

where NE and DE are in kilocalories per kilogram DM; EE is in percent DM; ST is starch in percent DM; and ADF is in percent DM. The determined mean DE value of each ingredient was used to calculate the NE value.

Statistical Analyses

All data for the experiment were analyzed using analysis of variance (**ANOVA**) with the Proc MIXED procedure of SAS (SAS Institute Inc., Carry, NC). Diet was treated as the only fixed effect and period and chamber as random effects. The LSMEANS statement with Tukey's adjustment was used to separate mean values. To eliminate the effect of ME intake, the THP and RE data were adjusted for each collection period by covariance analysis for ME intake of 528 kcal·kg $BW^{0.60−1}·d^{−1}$ (mean value for the experiment).

RESULTS

Chemical Composition of Ingredients and Diets

The analyzed chemical composition (DM basis) of ingredients and diets is shown in Tables 1 and 2, respectively. Compared with FFRB and DFRB, the CGF and CGM had a greater CP content. The analyzed content of EE in FFRB was the highest among the 6 ingredients. The starch in FFRB (29.1%) was similar to that in DFRB (27.9%). The starch content in CGM was 16.2%, which was 52.8% greater than that in CGF. The TDF content in CGF was 47.8%, which was 62.6%, 22.3%, and 28.2% greater than that in FFRB, DFRB, and CGM, respectively. The SDF content in FFRB was greater than that in DFRB, CGF, CGF, and CGM. Compared with FFRB, CGF, and CGM, DFRB contained the highest ADF content. Among the test ingredients, the 2 corn products, CGM and CGF, contained greater levels of Leu, Val, Ala, Glu, and Pro. In addition, Lys, Phe, Thr, Gly, and Ser content in CGM were the highest among the test ingredients.

The CGF and CGM diets contained greater CP content than other diets and the FFRB diet contained greater EE content than other diets (Table 2). The NDF content was the lowest in the basal diet but similar in the FFRB, DFRB, CGF, and CGM diets. In addition, the ratio of SDF to TDF was higher in the FFRB diet and the ADF was higher in the DFRB diet.

Apparent Total Tract Digestibility of Nutrients and Nitrogen Balance for Diets

The ATTD of DM, GE, and OM were the greatest ($P < 0.01$) in pigs fed the basal diet (Table 3). The ATTD of DM, GE, and OM in pigs fed the DFRB diet were lower ($P < 0.01$) compared with the basal and FFRB diets. Similarly, the ATTD of NDF and ADF (35.3% and 19.8%, respectively) in the DFRB diet were the lowest ($P < 0.01$) when compared with other dietary treatments, but there were no significant differences for the ATTD of NDF among the basal, FFRB, CGF, and CGM diets (average 62.0%). The ATTD of EE was the greatest ($P < 0.01$) in the FFRB diet (66.5%), and there were no significant differences among the basal, DFRB, CGF, and CGM diets (42.4% to 50.3%). The ratio of urinary energy to DE was greater ($P < 0.01$) in the CGM diet than that in the basal and FFRB diets. However, methane energy, expressed as a percentage of DE, was greater ($P < 0.01$) in the basal, CGF, and CGM diets than that in the FFRB diet. Consequently, the ME:DE ratio was lower ($P < 0.01$) in pigs fed the CGM diet (95.7%) when compared with those fed the basal and FFRB diets, and there were no significant differences among the basal, FFRB, and CGF diets (average 97.4%).

The nitrogen intake (39.9 to 49.1 g/d) increased with DM intake of pigs and CP content of diets. The nitrogen output from feces was the lowest ($P < 0.01$) in the basal diet (4.7 g/d), and there were no significant differences among the FFRB, DFRB, CGF, and CGM diets (average 8.6 g/d). Urinary nitrogen output was the highest ($P < 0.01$) in the CGM diet (17.3 g/d), and there were no significant differences among the basal, FFRB, DFRB, and CGF diets (average 8.4 g/d). In addition, no significant differences in retained nitrogen content (average 24.4 g/d) were observed among dietary treatments.

Energy Balance and Energy Values for Experimental Diets

The energy balance in pigs and DE, ME, and NE of experimental diets are presented in Table 4. The THP was lower ($P < 0.01$) in pigs fed the basal diet (286 kcal·kg $BW^{0.6−1}·d^{−1}$) than that in pigs fed the DFRB, CGF, and CGM diets (307 to 311 kcal·kg $BW^{0.6−1}·d^{−1}$). Pigs fed the FFRB diet had lower THP than pigs fed the DFRB diet. No significant differences were observed for FHP (188 kcal·kg $BW^{0.6−1}·d^{−1}$ on average) among treatments.

Table 1. Analyzed chemical composition of ingredients (DM basis)

	Ingredients[1]					
Item	Corn	SBM	FFRB	DFRB	CGF	CGM
GE, kcal/kg DM	4,465	4,639	5,206	4,132	4,598	4,431
CP, %	9.0	48.2	15.8	16.7	24.1	26.4
Ether extract, %	2.9	1.6	19.0	1.1	4.8	1.8
Starch, %	71.6	3.4	29.1	27.9	10.6	16.2
TDF[2], %	10.7	25.4	29.4	39.1	47.8	37.3
SDF[3], %	1.2	4.8	4.9	1.5	3.3	2.3
IDF[4], %	9.5	20.5	24.5	37.6	44.5	35.0
SDF/TDF, %	11.2	19.0	16.6	3.7	6.9	6.1
NDF, %	9.6	12.7	22.1	33.5	32.3	32.9
ADF, %	2.5	7.1	9.5	20.8	9.0	10.0
CF, %	–	–	8.7	20.9	10.7	16.2
Ash, %	1.2	6.3	8.8	11.5	6.6	6.9
Ca, %	0.02	0.40	0.24	0.11	0.51	0.03
Total P	0.31	0.73	1.70	1.28	1.04	1.29
Indispensable AA, %						
Arg	0.26	3.60	0.83	0.70	0.71	0.86
His	0.27	1.29	0.41	0.42	0.79	0.70
Leu	1.03	3.77	0.95	1.04	2.00	2.01
Ile	0.27	2.16	0.46	0.44	0.69	0.79
Lys	0.28	3.18	0.81	0.65	0.76	0.94
Met	0.22	0.74	0.32	0.28	0.42	0.48
Phe	0.45	2.52	0.68	0.69	0.81	1.00
Thr	0.32	1.96	0.56	0.52	0.86	0.98
Trp	0.43	0.43	0.28	0.34	0.29	0.29
Val	0.47	2.33	0.88	0.85	1.35	1.44
Dispensable AA, %						
Ala	0.39	1.35	0.57	0.61	1.14	1.27
Asp	0.56	5.46	1.43	1.19	1.27	1.56
Cys	0.21	0.70	0.76	0.70	0.79	0.70
Glu	1.54	8.55	1.92	2.02	3.27	3.27
Gly	0.25	1.64	0.59	0.53	0.77	0.95
Pro	0.86	2.58	0.73	0.75	2.24	1.91
Ser	0.39	2.38	0.61	0.61	0.82	1.09
Tyr	0.36	1.61	0.50	0.43	0.64	0.58

[1] SBM = soybean meal; FFRB = full-fat rice bran; DFRB = defatted rice bran; CGF = corn gluten feed; CGM = corn germ meal.

[2] TDF = total dietary fiber.

[3] SDF = soluble dietary fiber.

[4] IDF = insoluble dietary fiber.

However, the RE and RE_L in pigs fed the basal and FFRB diets were greater ($P < 0.01$) than those fed the DFRB, CGF, and CGM diets. The RE_P in pigs fed the CGF diet was greater ($P < 0.05$) compare with those fed the CGM diet. The value of RQ was not affected by dietary treatments and was markedly lower during the FHP period (0.82 vs. 1.07). The adjusted THP was greater ($P < 0.01$) in pigs fed the DFRB, CGF, and CGM diets compare with those fed the basal and FFRB diets. The adjusted total RE was greater ($P < 0.01$) in pigs fed the basal and FFRB diets compare with those fed the DFRB, CGF, and CGM diets. Pigs fed the CGF diet had greater ($P < 0.05$) adjusted RE_P than those fed FFRB and CGM diets. The adjusted RE_L was greater ($P < 0.01$) in pigs fed the basal and FFRB diets compared with those fed the DFRB, CGF, and CGM diets.

The NE:ME ratio was greater ($P < 0.01$) in pigs fed the FFRB diet (81.8%) when compared with those fed the DFRB, CGF, and CGM diets (average 77.2%). No significant differences were observed for NE:ME ratio between the FFRB and basal diets. The DE of basal and FFRB diets was greater ($P < 0.01$) than that of the DFRB, CGF, and CGM diets. The ME and NE contents in the basal and FFRB diets were the greatest ($P < 0.01$) followed by the CGF and CGM diets. No differences were

Table 2. Composition and nutrient content of experimental diets

	Dietary treatment[1]				
Item	Basal	FFRB	DFRB	CGF	CGM
Ingredients, %					
Corn	71.67	49.58	49.58	49.58	49.58
Soybean meal	24.95	17.26	17.26	17.26	17.26
FFRB	–	30.00	–	–	–
DFRB	–	–	30.00	–	–
CGF	–	–	–	30.00	–
CGM	–	–	–	–	30.00
Dicalcium phosphate	0.90	0.90	0.90	0.90	0.90
Limestone	0.90	0.90	0.90	0.90	0.90
Salt	0.35	0.35	0.35	0.35	0.35
Vitamin and mineral premix[2]	0.50	0.50	0.50	0.50	0.50
Lys-HCl	0.50	0.35	0.35	0.35	0.35
Met	0.07	0.05	0.05	0.05	0.05
Thr	0.16	0.11	0.11	0.11	0.11
Calculated composition, as-fed basis					
ME, kcal/kg	3,279	3,167	2,890	3,042	3,117
CP, %	15.7	15.1	15.3	17.6	18.0
Analyzed composition[3], DM basis					
GE, kcal/kg DM	4,448	4,661	4,383	4,474	4,424
CP, %	20.0	18.3	18.8	20.8	22.1
Ether extract, %	3.3	7.5	2.8	3.4	2.7
Starch, %	53.9	46.4	45.2	39.7	41.9
TDF, %	14.1	18.6	21.7	24.5	21.2
SDF, %	2.1	2.9	1.9	2.4	2.1
IDF, %	12.0	15.7	19.8	22.1	19.1
SDF/TDF, %	14.8	15.7	8.6	10.0	10.0
NDF, %	12.9	20.1	22.2	21.3	22.1
ADF, %	4.13	5.55	10.66	6.49	6.23
Ash, %	5.03	6.76	7.68	6.43	6.41
Ca, %	0.65	0.68	0.65	0.76	0.63
Total P, %	0.52	0.87	0.75	0.70	0.76

[1] Basal = corn–soybean meal basal diet; FFRB = full-fat rice bran diet; DFRB = defatted rice bran diet; CGF = corn gluten feed diet; CGM = corn germ meal diet.

[2] Premix provided the following per kilogram of complete diet: vitamin A as retinyl acetate, 5,512 IU; vitamin D_3 as cholecalciferol, 2,200 IU; vitamin E as DL-alpha-tocopheryl acetate, 30 IU; vitamin K_3 as menadione nicotinamide bisulfite, 2.2 mg; vitamin B_{12}, 27.6 µg; riboflavin, 4 mg; pantothenic acid as DL-calcium pantothenate, 14 mg; niacin, 30 mg; choline chloride, 400 mg; folacin, 0.7 mg; thiamin as thiamine mononitrate, 1.5 mg; pyridoxine as pyridoxine hydrochloride, 3 mg; biotin, 44 µg; Mn as MnO, 40 mg; Fe as $FeSO_4 \cdot H_2O$, 75 mg; Zn as ZnO, 75 mg; Cu as $CuSO_4 \cdot 5H_2O$, 25 mg; I as KI, 0.3 mg; Se as Na_2SeO_3, 0.3 mg.

[3] TDF = total dietary fiber; SDF = soluble dietary fiber; IDF = insoluble dietary fiber.

observed for the ME and NE of CGF and CGM diets.

Apparent Total Tract Digestibility of Nutrients and Energy Content for Ingredients

The ATTD of nutrients and DE, ME, and NE content of test ingredients are presented in Table 5. The ATTD of GE in pigs fed FFRB (72.3%) and CGM (72.9%) was greater when compared with those fed DFRB (45.1%) and CGF (57.6%). The ATTD of CP in pigs fed CGM (80.5%) was greater when compared with those fed FFRB (57.1%) and DFRB (54.9%). The ATTD of NDF and ADF in pigs fed DFRB (18.9% and 3.5%, respectively) were lowest among the 4 ingredients. The NE:ME ratio (82.4%) was greater in the FFRB than in the DFRB (60.8%). The NE contents of FFRB, DFRB, CGF, and CGM determined using the IC method were 2,952, 1,100, 1,747, and 2,079 kcal/kg DM, respectively, whereas the corresponding NE values calculated using the published equations were 2,853, 1,124, 1,684, and 2,043 kcal/kg DM, respectively. The NE contents of FFRB, CGF, and CGM determined using the IC method were 3.5%, 3.8%, and 1.8% greater, respectively, than the predicted values, whereas NE of DFRB using the IC method was 2.1% lower than the predicted values.

Table 3. Effect of diet characteristics on nutrient and energy digestibility and nitrogen balance in growing pigs (DM basis)

	Dietary treatment^{1}						
Item	Basal	FFRB	DFRB	CGF	CGM	SEM	*P*-value
BW, kg	36.2^{b}	36.1^{b}	34.7^{b}	34.9^{b}	40.8^{a}	0.9	<0.001
DM intake, kg/d	1.25^{c}	1.28^{c}	1.40^{a}	1.31^{bc}	1.39^{ab}	0.02	<0.001
ATTD, %							
DM	89.3^{a}	81.0^{bc}	74.1^{d}	78.9^{c}	84.2^{b}	1.0	<0.001
GE	88.8^{a}	81.7^{bc}	74.9^{d}	78.7^{cd}	83.8^{b}	1.1	<0.001
CP	88.2^{a}	77.5^{c}	76.3^{c}	80.8^{bc}	84.7^{ab}	1.8	<0.001
NDF	65.5^{a}	61.8^{a}	35.3^{b}	57.1^{a}	63.4^{a}	2.3	<0.001
ADF	62.8^{a}	42.24^{b}	19.79^{c}	50.2^{b}	64.2^{a}	3.0	<0.001
Ether extract	50.3^{b}	66.5^{a}	48.4^{b}	47.8^{b}	42.4^{b}	2.9	<0.001
OM	90.8^{a}	83.7^{bc}	77.3^{d}	80.4^{cd}	85.7^{b}	1.0	<0.001
Urinary energy, % of DE	2.09^{b}	1.79^{b}	2.45^{ab}	2.17$^{ab;}$	3.60^{a}	0.39	0.017
Methane energy, % of DE	0.38^{a}	0.22^{b}	0.30^{ab}	0.57^{a}	0.52^{a}	0.08	0.009
ME, % of DE	97.4^{a}	97.9^{a}	97.2^{ab}	97.1^{ab}	95.7^{b}	0.4	0.009
Nitrogen balance							
Intake, g/d	39.9^{cd}	37.5^{d}	42.0^{bc}	43.5^{b}	49.1^{a}	0.7	<0.001
Fecal output, g/d	4.7^{b}	8.4^{a}	10.0^{a}	8.4^{a}	7.5^{a}	0.7	<0.001
Urinary output, g/d	9.6^{b}	5.7^{b}	8.7^{b}	9.7^{b}	17.3^{a}	1.2	<0.001
Retention, g/d	25.6	23.3	23.4	25.5	24.4	1.5	0.629

$^{a–d}$Means within a row with different superscripts differ ($P < 0.05$).

^{1}Basal = corn–soybean meal basal diet; FFRB = full-fat rice bran diet; DFRB = defatted rice bran diet; CGF = corn gluten feed diet; CGM = corn germ meal diet.

DISCUSSION

Chemical Composition of Ingredients

Chemical composition of the FFRB (Sauvant et al., 2004; Shi et al., 2015), DFRB (NRC, 2012; Stein et al., 2015), CGF (Anderson et al., 2012; Wang et al., 2014; Shi et al., 2015), and CGM (Anderson et al., 2012; Stein et al., 2016) was within the range of values reported in previous work. There were great variations in the chemical composition of feedstuffs among these published literatures. Variety, origin, and processing technology are cited as primary reasons for variations in chemical composition of feedstuffs (Chen et al., 2016; Rojas and Stein, 2017). For example, the EE content in FFRB varies between 14% and 24% based on the variety of rice and the type of milling used (Kaufmann et al., 2005; Shi et al., 2015). However, DFRB contains 2% to 4% fat due to removal of fat from rice bran during solvent extraction (Stein et al., 2016). In accordance with the variation in EE content, the contents of CP, TDF, NDF, and ADF in DFRB were markedly higher than that in FFRB. The nutrient content in CGF is more variable than that in other corn coproducts because CGF contains a number of product streams from the wet milling industry. Wang et al. (2014) analyzed chemical composition of 10 CGF samples and found that the NDF content had huge variation (37% to 53%, DM basis). Stein et al. (2016) reviewed nutrient composition of corn coproducts and found that the average concentrations (DM basis) of TDF and NDF in CGF were 36.5% and 39.6%, respectively, and in CGM were 46.9% and 56.1%, respectively. Anderson et al. (2012) reported the concentration (DM basis) of TDF and NDF in CGF was 40.1% and 42.7%, respectively, and in CGM were 47.8% and 61.1%, respectively. However, the concentrations of TDF and NDF (30.8% and 27.2% of DM, respectively) in CGF as reported in NRC (2012) were lower than those observed in this study.

Apparent Total Tract Digestibility of Nutrients and Nitrogen Balance for Diets

The ATTD of DM and GE is negatively correlated to dietary fiber content (Noblet and Le Goff, 2001; Jha and Berrocoso, 2015). In the current study, the reduced DM, OM, and energy digestibility in pigs fed diets containing DFRB, CGF, and CGM are in accordance with the reduced DE, ME, and NE of diets containing DFRB, CGF, and CGM. The negative effect of dietary fiber was partly attenuated in the FFRB diet because of its higher fat content. Similarly, the ATTD of DM, OM, and GE of the 4 ingredients with relative high fiber content used in the current study were lower

Table 4. Effect of diet characteristics on energy balance of growing pigs

	Dietary treatment[1]						
Item	Basal	FFRB	DFRB	CGF	CGM	SEM	*P*-value
Energy balance[2], kcal·kg $BW^{0.6-1}·d^{-1}$							
ME intake	544^{a}	537^{ab}	518^{b}	514^{b}	515^{b}	6	0.003
THP	286^{c}	288^{bc}	311^{a}	307^{ab}	307^{ab}	5	0.003
Adjusted THP	277^{b}	282^{b}	315^{a}	313^{a}	312^{a}	6	<0.001
FHP[3]	182	189	188	193	186	5	0.529
RE[4], kcal·kg $BW^{0.6-1}·d^{-1}$							
RE_P	103^{ab}	94^{ab}	96^{ab}	109^{a}	91^{b}	5	0.044
RE_L	156^{a}	156^{a}	113^{b}	97.3^{b}	118^{b}	7	<0.001
Total	259^{a}	250^{a}	209^{b}	207^{b}	209^{b}	5	<0.001
Adjusted RE_P	98^{ab}	91^{b}	98^{ab}	111^{a}	93^{b}	5	0.040
Adjusted RE_L	152^{a}	154^{a}	114^{bc}	101^{c}	120^{b}	8	<0.001
Adjusted total	250^{a}	245^{a}	212^{b}	213^{b}	213^{b}	4	<0.001
RQ							
Fed state	1.07	1.05	1.08	1.07	1.06	0.01	0.183
Fasted state[3]	0.82	0.83	0.80	0.84	0.80	0.01	0.103
Energy utilization, %							
NE/ME	80.9^{ab}	81.8^{a}	76.7^{c}	78.1^{bc}	76.9^{c}	1.1	0.001
Energy values, kcal/kg DM							
DE	$3,947^{a}$	$3,805^{ab}$	$3,284^{d}$	$3,520^{c}$	$3,709^{b}$	47	<0.001
ME	$3,843^{a}$	$3,725^{a}$	$3,191^{c}$	$3,414^{b}$	$3,549^{b}$	40	<0.001
NE_1[5]	$3,110^{a}$	$3,047^{a}$	$2,450^{c}$	$2,669^{b}$	$2,729^{b}$	42	<0.001
NE_2[5]	3,065	2,978	2,390	2,575	2,677	–	–
Predicted NE[5]	2,857	2,792	2,297	2,464	2,586	–	–

[a–d]Means within a row with different superscripts differ ($P < 0.05$).

[1]Basal = corn–soybean meal basal diet; FFRB = full-fat rice bran diet; DFRB = defatted rice bran diet; CGF = corn gluten feed diet; CGM = corn germ meal diet.

[2]THP = total heat production; FHP = fasting heat production; adjusted THP means the THP was adjusted for an ME intake of 528 kcal·kg $BW^{0.60-1}·d^{-1}$ (mean value for the experiment) by covariance.

[3]FHP was calculated using the equation for THP with gas concentrations and air flow obtained from only the last 8-h heat production measurement from days 19 to 20 (i.e., from 22:30 to 06:30 h). To base production using the same time span as used for THP, the 8-h heat production was extrapolated to a 24-h period. Similarly, the RQ in fasted state was calculated as the ratio between CO_2 production and O_2 consumption (which was extrapolated to a 24-h period).

[4]RE = retained energy; RE_P = retained energy as protein (kcal·kg $BW^{0.6-1}·d^{-1}$) = [nitrogen intake (g) − nitrogen in feces (g) − nitrogen in urine (g)] × 6.25 × 5.70 (kcal/g)/$BW^{0.6}$; RE_L = retained energy as lipids (kcal·kg $BW^{0.6-1}·d^{-1}$) = [RE (kcal) − retained energy as protein (kcal)]/$BW^{0.6}$. Adjusted RE_P, RE_L, and RE means the RE_P, RE_L, and RE was adjusted for an ME intake of 528 kcal·kg $BW^{0.60-1}·d^{-1}$ (mean value for the experiment) by covariance, respectively.

[5]NE_1 or NE_2 (kcal/kg DM) = [RE (kcal/d) + FHP (kcal/d)]/DMI (kg/d), where FHP was from individual FHP measured in this experiment and FHP of Noblet et al. (1994; FHP = 179 kcal·kg $BW^{0.6-1}·d^{-1}$), respectively; predicted NE (kcal/kg DM) = 0.700 × DE (kcal/kg DM) + [(1.61 × ether extract (%) + 0.48 × starch (%) − 0.91 × CP (%) − 0.87 × ADF (%)] × 10.

than most conventional cereal and protein ingredients including corn, polished white rice, wheat, and soybean meal (Jaworski et al., 2015; Stein et al., 2016). Digestibility of dietary fiber is more variable and typically lower than that of other nutrients such as starch, sugars, fat, and CP and is affected by the source of fiber in the diet (Noblet, 2007; Jha and Berrocoso, 2015). The greater ATTD of fiber component in FFRB than that in DFRB can be explained that FFRB contains more SDF, which is generally more easily, rapidly, and completely fermented than IDF (Urriola and Stein, 2010). Dietary fiber can hamper digestive enzymatic hydrolysis of CP and increase endogenous nitrogen excretion (Noblet and Le Goff, 2001), which explains the decrease in reduced digestibility of CP in pigs fed FFRB, DFRB, CGF, and CGM diets. Methane energy averaged 0.40% of DE and was consistent with the results of Noblet et al. (1994).

According to the design, the pigs fed diets with AA supplied above their daily requirements (relative to the energy supply), and they then maximized their nitrogen gain (average 24.4 g/d) with no difference between diets as confirmed in Table 3. The differences in urinary nitrogen excretion were also a consequence of the design, any nitrogen (or AA) in excess of digestible nitrogen (or AA) requirements being excreted in urine (Zervas and Zijlstra, 2002;

Table 5. Energy utilization and energy value of the 4 ingredients (DM basis)

	Ingredient[1]			
Item	FFRB	DFRB	CGF	CGM
ATTD, %				
GE	72.3	45.1	57.6	72.9
CP	57.1	54.9	70.7	80.5
NDF	58.7	18.9	53.0	61.6
ADF	23.9	3.5	41.4	65.0
OM	67.0	45.1	57.3	73.1
Energy utilization, %				
ME/DE	95.2	97.1	95.9	89.9
NE/ME	82.4	60.8	68.8	71.6
Energy values, kcal/kg DM				
DE	3,763	1,864	2,648	3,232
ME	3,580	1,810	2,540	2,905
NE	2,952	1,100	1,747	2,079

[1] FFRB = full-fat rice bran; DFRB = defatted rice bran; CGF = corn gluten feed; CGM = corn germ meal.

[2] The predicted NE was from Noblet et al. (1994), where NE (kcal/kg DM) = 0.700 × DE (kcal/kg DM) + [(1.61 × ether extract (%) + 0.48 × starch (%) − 0.91 × CP (%) − 0.87 × ADF (%)] × 10.

Bindelle et al., 2009) with an important consequence on the ME:DE ratio of the diet or the ingredient. Accordingly, the greater nitrogen intake led to more urinary nitrogen excretion (greater urine energy), which resulted in a low ME:DE ratio in the CGM diet.

Energy Balance and Energy Values for Experimental Diets

In our study, the HP (expressed in kcal·kg BW$^{0.60-1}$·d^{-1}) was adjusted for a ME intake of 528 kcal·kg BW$^{0.6-1}$·d^{-1} (mean value for the experiment) using the covariance to eliminate the effect of ME intake on HP. The results of the lower adjusted HP in pig fed the FFRB diet than in pigs fed the DFRB, CGF, and CGM diets were in agreement with the results of Noblet et al. (2001) and Li et al. (2017b). This indicated that dietary lipids had a lower heat increment and therefore had higher utilization efficiency (Li et al., 2017b). The RE and RE$_L$ were greater in pigs fed the FFRB and was due in part to lower HP as a result of the greater EE content in the FFRB. There are controversial results about the effect of dietary fiber on HP. In some studies, significant increases in HP were observed with increased inclusion level of dietary fiber (Ramonet et al., 2000; Rijnen et al., 2003), whereas similar (Heo et al., 2014; Kim and Nyachoti, 2017) or decreased HP values (Jaworski et al., 2016) were observed in other studies. It is possible that feeding diets high in fiber does not affect THP, but it may affect the components of HP (e.g., due to changes in physical activity; Le Goff et al., 2002). However, physical activity was not measured in the current experiment. The FHP was not affected by diets, which was consistent with the results of Li et al. (2017a) and Velayudhan et al. (2015). The value of FHP (182 to 193 kcal·kg BW$^{0.6-1}$·d^{-1}) was similar to our previous work using the same method (Zhang et al., 2014; Li et al., 2017a,b).

The values of energetic efficiency were within the range of values reported in previous studies (Wang et al., 2014; Shi et al., 2015; Velayudhan et al., 2015; Li et al., 2017a; Kim and Nyachoti, 2017). The greater NE:ME ratios in the FFRB diet than in the DFRB, CGF, and CGM diets can be explained by the differences in efficiencies of ME utilization between nutrients with the highest values for fat (90%) and starch (82%) and the lowest (60%) for dietary fiber and CP (Noblet et al., 1994). The NE:ME ratio (76.7% to 81.8%) of the 5 experimental diets were greater than the values (74%) reported by Noblet et al. (1994). This difference in NE:ME ratio can be explained by the greater FHP (188 kcal·kg BW$^{0.6-1}$·d^{-1}) measured in the current experiment than the value (179 kcal·kg BW$^{0.6-1}$·d^{-1}) used by Noblet et al. (1994).

The NE values of diets determined using the IC method were greater (relative error: average 7.2%) than the predicted values, which is due to measured FHP were slightly higher than the values obtained with the FHP estimated by Noblet et al. (1994). This observation emphasizes the fact that the estimation of NE for maintenance (or FHP) directly influences the NE value of diets. When the individual FHP measured in this experiment was replaced by 179 kcal·kg BW$^{0.6-1}$·d^{-1}, the NE value of diets were close (relative error: average 4.9%) to the predicted NE value.

Apparent Total Tract Digestibility of Nutrients and Energy Content for Ingredients

The low ME:DE ratio for CGM illustrated the impact of the design of the trial on the results. In other words, the methodology used here with an oversupply of protein (resulting in greater urinary nitrogen excretion) in the CGM diet provided an ME and calculated NE estimate that is lower and not representative of what would be observed in a "normal" CP content (for growing pigs) diet.

The DE and ME of FFRB, DFRB, CGF, and CGM determined in the current experiment were similar to those reported in previous studies (Anderson et al., 2012; Wang et al., 2014; Shi et al., 2015; Stein et al., 2016). However, to our knowledge, this is the first report of NE contents of FFRB, DFRB, CGF, and CGM fed to swine. The NE of FFRB, DFRB, CGF, and CGM determined using the IC method were similar to the NE calculated using the prediction equation. The prediction equation utilized adequately estimated the NE of ingredients. Similar results were obtained by Ayoade et al. (2012) and Li et al. (2015), who found no difference between determined and predicted values.

In conclusion, pigs fed the fiber-rich ingredients had greater HP and lower nutrient digestibility. However, pigs fed FFRB diets containing greater fat content had a lower heat increment and, therefore, higher utilization efficiency. The NE:ME ratio ranged from 71.6% to 82.4%. The NE of FFRB, DFRB, CGF, and CGM determined using the IC method were 2,952, 1,100, 1,747, and 2,079 kcal/kg DM, respectively.

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